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Study on impact of runoff on saltwater intruding from the North Branch in the Changjiang Estuary

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Abstract

A two-dimensional hydrodynamic force-salinity transport model in Yangtze River Estuary is established on the basis of analyzing the measured data and the adoption of MIKE21 model.This model is used to study the average daily distribution and changing patterns of the saline groups (i.e. salinity water lenses) in the South Branch that are from the North Branch while only the saltwater intrusion from the North Branch is considered. The impact of runoff on the transport of intruding saline group and its salinity changes is studied using the established model. It is found by the study that the average location and time changes for tidal cycles of intruding saline group cores in watercourses in the Estuary are line up to the Gompertz model. And,the non-linear relationship of parameters and runoff volume in the Gompertz model is available.

Keywords: Changjiang Estuary; intruding saline group (salinity water lenses) ; numerical simulation; Gompertz model; Transport pattern;

1. Introduction

The saltwater intrusion in the Changjiang Estuary has exerted a deep impact on the estuarine circulation, maximum turbid belt and sandbar change, so does on industry and agriculture, domestic water and fishery in Shanghai and Jiangsu. The runoff is a decisive factor to control salt-water encroachment in Changjiang Estuary. Based on salt water intrusion measured data and many-year runoff volume & water-level data, Mao Zhichang (1994) found the intensity of saltwater intrusion is mainly related to the runoff volume of the Changjiang River in the dry season. The annual runoff volume in the Datong Station is then divided into the runoff volume in the flood

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season and runoff volume in dry seasons. The dry-season runoff volume includes four hydrologic years: rich, general, dry and quite dry runoff volumes. This division is more indicating the salt tidal activity in the Changjiang Estuary. Zhu Jianrong(2013) studied the salt water intrusion of Changjiang Estuary in the dry season. In the calculation, considering the influence of such major water diversion projects as the Three Gorges, the non-water taking days were known for Dongfeng Xisha Reservoir based on the Datong Station day-by-day runoff volume in the dry season during 1978-1979 with guarantee rate of upstream runoff. the salinity line was proposed as the especially important basis for capacity design of reservoir. Shen Huanting(2000)studied changes of Changjiang Estuary runoff and salinity and their mutual relation using spectral analysis based on series of runoff data from the Datong Hydrologic Station and salinity data from the pilot boat station. Xiao Chengyou(1998) found the change of salinity in Wusong Station lagged 6-9 days behind that of runoff in Datong Station by comparing the salinity data from Wusong Station with the runoff data from Datong Station. Hou Chengcheng(2013) analyzed the response time of Changjiang Estuary salt-water intrusion to the runoff changes in the Datong station in different tide types, finding a certain difference in the response time of different tide types to runoff pulses. Zhu Jianrong(2008) found that upstream runoff has a good exponential relation with maximum salinity within a half month in such stations as Liuxiao and Xinjian by the numerical simulation tests. Zhu Jianrong(2013) revised the runoff volume in Datong Station based on Three Gorges Project, South-to-North Water Diversion project and diversion & drainage projects along the Changjiang River, and figured out the most non-water-taking days for the Dongfeng Xisha reservoir by the 1978-1979 extreme dry season as a hydrological calculating year.

Above studies mainly focus on the response relation of intruding saltwater changes with runoff and tidal range, as well asand mutual relation of salinity and runoff in some stations suffered from saltwater intrusion in the south branch in the Changjiang Estuary(Xiao Chengyou,2000). The in-depth studies on runoff volume changes are lacked for activity of saline group intruding from the north branch and changes of saline group concentration in the south branch. These changes will be studied further using the Changjiang Estuary 2D hydrological-salinity transport model.

2. Mathematical model

2.1 Governing equations

MIKE21 adopts Temperature/Salinity (TS) Module to complete the numerical calculation of temperature and salinity diffusion. In Cartesian coordinates, the three-dimensional salinity transport equation is:

$$\frac{\partial s}{\partial t}+\frac{\partial us}{\partial x}+\frac{\partial vs}{\partial y}+\frac{\partial ws}{\partial z}=F_s++\frac{\partial}{\partial z}\left(D_v\frac{\partial s}{\partial z}\right)+s_sS \tag{1}$$

Where: s is Salinity; D_v is vertical diffusion coefficient of salinity; s_s is salinity discharge from point source; F_s is horizontal salinity diffusion, which can be defined as

$$F_s=\left[\frac{\partial}{\partial x}\left(D_h\frac{\partial}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_h\frac{\partial}{\partial y}\right)\right]s \tag{2}$$

Where: $D_{h:}$ horizontal salinity diffusion coefficient.

2.2 Boundary conditions and numerical methods

In order to facilitate the study of the intrusion from the north branch, following models A, B1 and B2 (Fig.1) were defined. Model A has the maximum range. In a low-flow period, the upstream tidal current boundary is Datong Station in Anhui Province, which is about 500km away from Xuliuting in the Yangtze River Estuary. The downstream boundaries in the open sea have a north boundary at approximately 32.5° degrees northern latitude (Lusi Harbor), a south boundary at 29.5° degrees north latitude (south of Zhoushan Island) and an east boundary which is 50 meters in depth and 124.5° east longitude in the open sea. The entire range of this model is about 700km in east-west direction, about 350km in north-south direction, covering an area of approximately 105000km^2 .

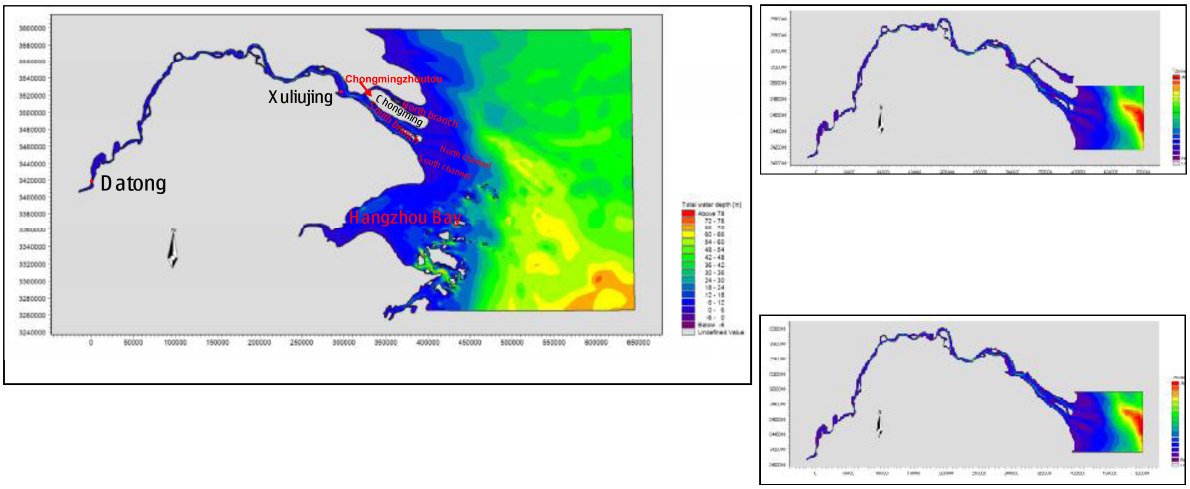


Fig. 1. (left) the topographical map for schematic A; (right) the topographical map r schematic B1 (upside) and B2 (underside).

As to model B1 in this paper, it has an upper boundary in Datong, a downstream boundary in the north branch near Lianxing Harbor, an east boundary in the south branch which is 40m in isobath and about 100km away from the entrance, a north boundary in the northern part of Chongming Dongtan, and a south boundary near Luchao Harbor. In addition, in order to facilitate the control of the intensity of intrusion, model B2 was constructed based on Model B1. Model B2 has its north boundary near Chongmingzhoutou and other boundaries like model B1.

In this study, Model A has 115780 grids and 61246 nodes. The maximum grid spacing in the open sea is 8000 meters and the minimum grid spacing within the harbor entrance is 200 meters. The grid spacing gradually decreases from the open sea to the entrance. Model B1 has 74115 grids and 39603 nodes. The maximum grid spacing in the open sea is 2000meters. The grid size within the entrance is about the same in Model A. Model B2 has 32311 grids and 60368 nodes. Its grid spacing in the open sea is 2000 meters. Its grid size within the entrance is about the same size in model A.

The upstream Datong Boundaries of Model A, B1 and B2 are driven by the daily flows from February 11, 2002 to March 13, 2002. The boundary of Model A in the open sea is driven by hourly water levels from February 11, 2002 to March 13, 2002. The water level data is provided by East China Sea Model(Zhang Weisheng,2005) calculation. The flow of Qiangtangjiang boundary is set to 0m^3/s because of its small runoff volume. As to Model

B1, the open sea boundary in the south branch and entrance boundary in the north branch are driven by the water level process that was obtained from Model A 's hydrodynamic calculation results. For Model B2, the open sea boundary in the south branch and the Chongtou boundary in the south branch are driven by the water level process and flow process from Model A's hydrodynamic calculation results. The initial conditions of Models A, B1 and B2 adopt cold start and both their sea levels and flow rates are set to 0.

For Model A, its upstream salinity is 0. Its salinity boundary in open sea adopts the findings of previous studies where the south boundary adopts 15‰～30‰ salinity linear interpolation from west to east, the east boundary in the open sea adopts 30‰～35‰ salinity linear interpolation from south to north, the north boundary adopts 25‰～35‰ salinity linear interpolation from west to east. For models B1and B2, the salinity boundary in the north branch is obtained from the salinity computation results of Model A. The salinity in open sea of the south branch is set to 0.

Based on the simulation range of model A, this paper sets its initial salinity to 0 and initial salinity field of model A according to the salinity field that was obtained from a 3-month continuous simulation. For Models B1 and B2, the salinity boundary in the north branch was obtained from the salinity computation by model A. The salinity of the open sea in the south branch is set to 0 and a 3-month continuous calculation was also taken to create an initial field for salinity simulation.

Set model parameters:

Time step: Δt=30s.

The horizontal eddy viscosity coefficient is calculated with Smagorinsky formula which estimates the eddy viscosity according to velocity gradient.

The roughness field has a great impact on the tide tidal rate and tidal range. In this paper, the roughness rates had been repeatedly calibrated according to the depths of different areas and the roughness rate is determined to be $0.01+0.01/H$ outside the entrance and $0.015+0.015/H$ inside the entrance, where H is local water depth (with respect to the mean tide level).

The horizontal diffusion coefficient of the salinity has certain impact on the salinity field in the Yangtze River Estuary. The greater the level of the diffusion coefficient, the faster spread of salinity and the greater of the diffusion range are. According to repeated calculations and calibrations, the salinity diffusion coefficient is a constant value 100 m^2/s.

Model validation:

The computing time for model A, B1 and B2 is from 00 a.m., February 11, 2002 to 00 am March 13, 2002, which lasted for a month. The computation results of the last 15 days were adopted in the analysis. This period includes the typical tides types of full tide, spring tide and neap tide. Here, a percentage deviation model (Maréchal D., 2004) was adopted to evaluate the simulation of model A,B1 and B2 over sea level and flow rate.

The observation data of the salinity and tide levels in the Yangtze River Estuary in the first ten-day period of March (low-flow period) and the third ten-day period of September (flood period) are selected, of which the average volumes of runoff in Datong were 18000m^3/s in March and 44300m^3/s in September. The verification points of salinity and tides are the same. The verification time includes March 1 to March 2 for the full tide, March 4 to March 5 for moderate tide and March 8 to March 9 for slack tide. The test periods at each station in the selected period were basically over 27 hours.

Since Model B1 and B2 considered the intrusion from the north branch rather than the saltwater intrusion that was from outside the south branch entrance, Model B1 and B2 only tested the points in the north branch and upper section of south branch that were affected by the saltwater intrusion from the north branch. Model B1 includes Z1,Z2,Z3,Z4,Z6,Z7,Z8,Z9,Y4,Y5,Y6 and Model B2 includes Z3, Y4,Y5,Y6,Z4 (Shao yuchen ,2013).

The percentage deviation model was used again to evaluate the salinity simulation of Model A, B1 and B2. This simulation of tide level, tide flow and salinity were good. The PB values (Maréchal D.,2004) were generally less than 40. The models that we had constructed can satisfy our research requirements (Shao yuchen ,2013).

3. Results and discussion

3.1 Route setting for the transport of the intruding saline group from the north branch in the Changjiang River

In order to further study the transport of saline groups intruding from the north branch, the transport of saline groups in watercourses in the south branch are revealed by studying the down movement of core saline groups and change of salinity in watercourses in the south branch.

Route setting of saline group transport: The starting point of the route was from the tail of Baimaosha nearby to the place 40km away from the Estuary. The routes include crosswise b1, b2, b3 and b4 as shown in Figure 2-3, where, b1 is 100 kilometers long from the main watercourse in the south branch to the north channel of the Estuary; b2 is 100km or so from main watercourse in the south branch to the south channel to the north passage; b3 is 100km long or so from main watercourse in the south branch to the south channel to the south passage; and b4 is 100km long or so from the south branch main watercourse in the south branch to the erosion ditches along the upstream of the Xinqiao watercourse to the Xinqiao watercourse to the north channel.

3.2 Relation of runoff volumetransport and concentration of intruding saline groups with runoff volume

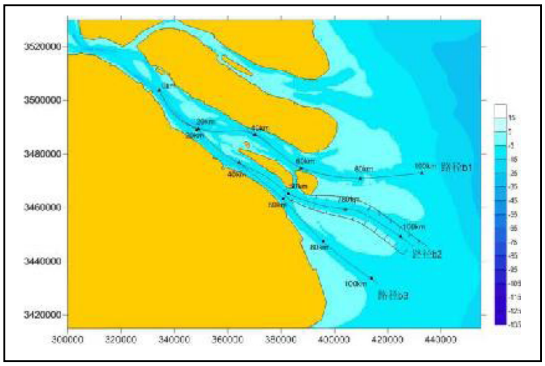


Fig. 2. Setting of routes b1, b2 and b3.

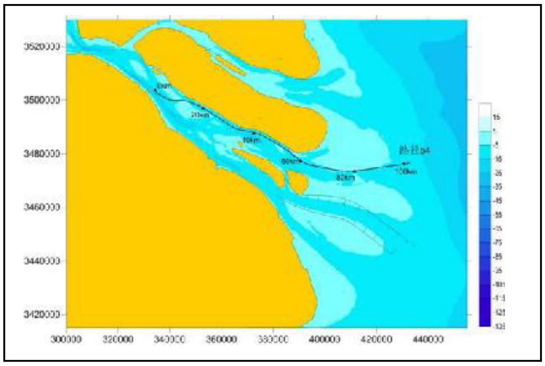


Fig. 3. Setting of route b4.

In order better to describe the transport of saline group cores, the Gompertz model is applied to fit the transports of saline group cores in routes in different runoff conditions. The mathematical expression of the Gompertz model curve as follows(Jiangchen et al.2002):

$$y = e^{(-be^{-kt})} \tag{3}$$

Where, t stands for time; a, b, and k all are parameters fitted out by the Gompertz model based on numerical simulation (a represents the limit value of the curve, and is the maximum displacement of saline group core theoretically, b mainly represents the initial value relative to the limit value; and k represents the discharging rate of saline groups). The bigger the k is, the faster the saline groups discharge, and more quickly the saline groups can reach the maximum theoretical displacement of the saline groups. In addition, Expression (3) is changed as follows because the saline groups move down from 00:00, the sixth day after the numerical simulation.

$$y = ae^{(-be^{-k(t-5)})}$$

(4)

By Expression (4), the changes of saline group core location at all levels of runoff volumes in Route b1 can be got by numerical simulation calculation. Table.1 shows the parameters corresponding to the Gompertz model fitting curve in Route b1.

Table 1 Calculating results of Gompertz model curve.

Runoff （m^3/s）	a	b	k
5000	35.389	7.878	0.519
7000	46.357	5.933	0.471
9000	57.326	3.986	0.423
11000	63.549	3.420	0.422
13000	69.772	2.854	0.421
15000	74.640	2.653	0.436
17000	79.508	2.451	0.450
19000	82.168	2.435	0.489
21000	84.829	2.419	0.527
23000	86.613	2.547	0.578
25000	88.398	2.675	0.628
27000	89.675	2.868	0.675
29000	90.952	3.061	0.723

The change of saline group core location shown in Fig. 4 can be known directly in runoffs in Route b1 based on parameters in Table 1. It is thus seen that the fitting results are more ideal.

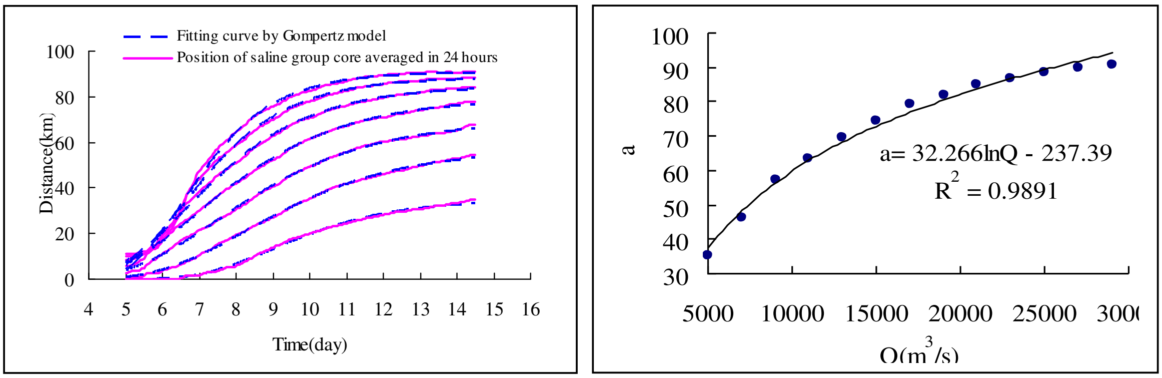


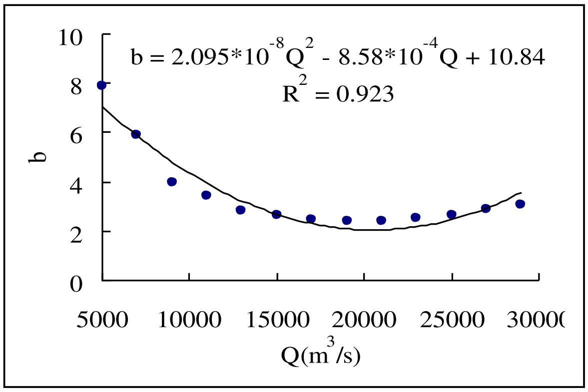
Fig. 4. Position of saline core in Route b1 in different runoff conditions.

Fig.5. Relation of Parameter *a* and runoff volume.

It is found from Table 1 that Parameter a has a positive correlation with the runoff value, convergent to 90 or so gradually, which indicates the bigger the runoff is, the bigger maximum theoretical displacement the saline group core reaches, with a maximum displacement of 90km or so. Moreover, the maximum theoretical displacement falls within 60km when the runoff is small (Q<11000 m^3/s), indicating in a small runoff, the saline group core can not come into open seas through the south branch within half month period; the mutual overlapping of saltwater intrusion in the first half and second half of a month causes the severe saltwater pollution. This is consistent with the results of Xiao Chengyou et al(1998).

The *b* has a complex relation with runoff value, reducing then increasing with the runoff. This may be because it slows down little by little with the runoff at an increasing rate. Parameter k represents the rate when saltwater core moves down to the maximum theoretical displacement; the bigger the *k* value is, the faster the saline group core reaches maximum theoretical displacement.

The functional relation of coefficients *a*, *b* and *k* with runoff volume *Q* in Route b1 is shown in Fig.5-7.



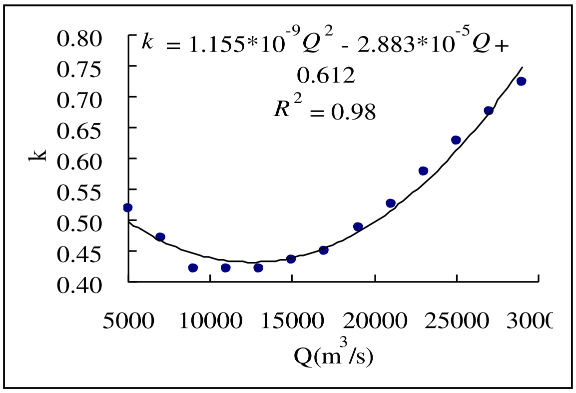


Fig. 6. Relation of Parameter *b* and runoff volume.

Fig. 7. Relation of Parameter *k* and runoff volume.

The fitting relation is:

$$a = 32.266 \ln Q - 237.39 \quad (5)$$

$$b = 2.095 \times 10^{-8} Q^2 - 8.582 \times 10^{-4} Q + 10.84 \quad (6)$$

$$k = 1.155 \times 10^{-9} Q^2 - 2.883 \times 10^{-5} Q + 0.612 \quad (7)$$

The relation of Gompertz model curve for saltwater core moving in other routes is shown in Table 2.

Table 2. Fitting relation of Parameters a, b and c with runoff volume in different routes.

Route	*a*	*b*	*c*
b1	$32.266\ln Q$-237.39	$2.095\times10^{-8}Q^2$-$8.582\times10^{-4}Q$+10.84	$1.155\times10^{-9}Q^2$-$2.883\times10^{-5}Q$+0.612
b2	$37.463\ln Q$-272.98	$2.311\times10^{-8}Q^2$-$9.632\times10^{-4}Q$+11.75	$1.733\times10^{-9}Q^2$-$5.371\times10^{-5}Q$+0.733
b3	$33.152\ln Q$-243.04	$1.699\times10^{-8}Q^2$-$8.488\times10^{-4}Q$+11.83	$1.140\times10^{-9}Q^2$-$3.635\times10^{-5}Q$+0.734
b4	$31.539\ln Q$-230.78	$2.077\times10^{-8}Q^2$-$8.389\times10^{-4}Q$+11.59	$0.734\times10^{-9}Q^2$-$0.945\times10^{-5}Q$+0.494

It is seen from Table 2 that the parameters *a*, *b* and *k* can be worked out based on runoff volume *Q* directly, then the change of saline group core location can be got at levels of runoff volumes based on Expression (6). By this way, the functional relation of saline group core moving down with *Q* and t is established, which can reflect the relation of speed of saline group moving down and *Q*. Table 2 shows the relational results of parameter and runoff volume *Q* of Gompertz model curve in routes. Based on the results, the changing curve of average moving location of tidal cycle is got for saline group core in Routes b1, b2, b3 and b4 in different runoff conditions of the improved Gompertz model fitting shown in Fig. 8-9. This is compared and verified with numerical simulation results.

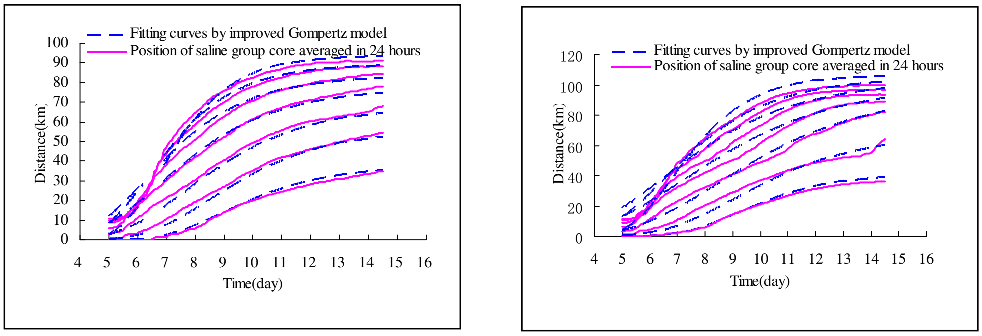


Fig. 8. Position of saline core in route b1(left) and b2(right)and the corresponding fitting curves by improved Gompertz model.

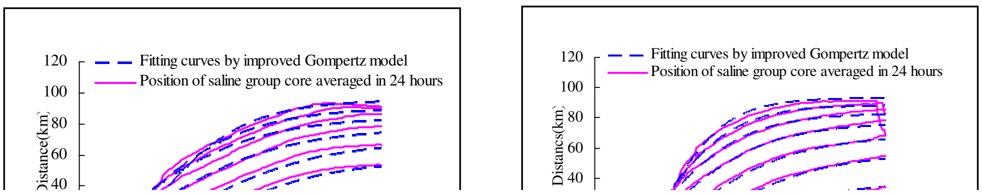


Fig. 9. Position of saline core in route b3(left) and b4(right)and the corresponding fitting curves by improved Gompertz model.

In Fig.4,fig.8,fig.9,the curves from the bottom to the top are respectively corresponding to the runoff rate of $5000m^3/s$,$9000m^3/s$,$13000m^3/s$,$17000m^3/s$,$21000m^3/s$,$25000m^3/s$,$29000m^3/s$.

4. Conclusions

It is thus seen that the Gompertz model fits the changes of average location of saline group core in 24 hours with time in different runoff volumes in different routes, which better coincides with numerical simulation calculating results. The verified Gompertz model may be used to study the transport of the saltwater intruding from the north branch in the south branch in the Changjiang Estuary.

The moving of intruding saline group and change of salinity in the north branch intrusion condition in the south branch in Changjiang Estuary are studied using model nesting method by establishing the 2D tide-salinity model of Changjiang Estuary. The impact of different runoff conditions on activity and salinity change of intruding saltwater is discussed. In different runoff volumes, the relation of average location and time of saline group core periods in watercourses is line up to the Gompertiz model. It will be available in other papers for the time for saline group core reaching the Estuary and average salinity change for saline group core tidal cycle in different runoff conditions.

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